Loss separation in soft magnetic composites

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Abstract

We report and discuss significant results on the magnetic losses and their frequency dependence in soft magnetic composites. Two types of bonded Fe-based materials have been characterized at different inductions from DC to 10 kHz and analyzed by extending the concept of loss separation and the related statistical theory to the case of heterogeneous materials. Starting from the experimental evidence of eddy current confinement inside the individual particles, the classical loss component is calculated for given particle size distribution. Taking then into account the contribution of the experimentally determined quasi-static (hysteresis) loss, the excess loss component is obtained and quantitatively assessed. Its behavior shows that the dynamic homogenization of the magnetization process with frequency, a landmark feature of magnetic laminations, is restrained in these materials. This results into a partial offset of the loss advantage offered by the eddy current confinement.

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I. INTRODUCTION

Three-dimensional flux paths and high frequencies are ubiquitous in modern electrical machines [1][2] and laminated cores may often prove inadequate. In fact, while inhibited from out-of-plane magnetization, soft magnetic laminations show a rapid increase of the power loss and fall into skin effect phenomena in the presence of harmonics and/or high working frequencies [3] [4]. Soft magnetic composites (SMCs) are therefore often proposed as convenient substitutes, their use appearing especially suited for devices like permanent magnet, claw-pole, and axial flux machines. While many literature efforts in these materials have been devoted to preparation methods and microstructural studies, with the aim of improving their manufacturing process, their mechanical properties, and their magnetic behavior[5][6], the analysis of the magnetic properties has mostly been performed on qualitative grounds [7][8], aiming at rapid exploitation in SMC machine core modeling [9]. For example, the important problem of loss calculation in such materials has been approached by use of polynomial interpolation methods [10][11], which are not accurate enough to predict the loss under highly distorted induction waveforms. De Wulf, et al. [12] have resorted to the concept of loss separation and attempted to apply Bertotti's statistical theory [13] to the frequency dependence of the energy loss in different types of SMCs. Their study was, however, limited to the maximum frequency of 100 Hz and their calculations disregard the actual heterogeneous structure of the material.

In this paper we present significant new results on the energy losses and their frequency dependence (DC – 10 kHz) in commercial soft Fe bonded composites. The experiments show that the sample cross-sectional area negligibly affects the loss at all frequencies. The classical loss component is therefore calculated for eddy current paths confined within the grains and the loss decomposition, leading to the determination of the hysteresis and excess losses, is accordingly performed . The excess loss is observed to depend on frequency in a quasi-linear fashion, in contrast with the square-root law usually observed in magnetic laminations. This provides evidence for correspondingly weakened dynamic homogenization of the magnetization process, ensuing from

68 combination of strong internal demagnetizing effects and lack of long-range eddy currents.

69

70   I. EXPERIMENTAL RESULTS AND DISCUSSION

71 Two commercial SMCs (Somaloy Prototyping and Somaloy 110i1P) have been investigated. The

72 first one (Material A) has the following physical properties: density δ = 7450 kg/m^3, electrical

73 resistivity ρ = 2.80·10^{-4} Ωm, average particle size $<s>$ = 114 μm. The second material (B) has quite

74 smaller particle size ($<s>$ = 29.5 μm) and lower filling factor (density δ = 7260 kg/m^3, electrical

75 resistivity ρ = 76·10^{-4} Ωm). Ring samples of mean diameter 50 mm and 25 mm were prepared for

76 magnetic testing. The larger rings had cross-sectional area S_1 = 5 $\times$ 5 mm^2, the smaller ones S_2 = 2.5

77 $\times$ 2.5 mm^2. Hysteresis loop and loss measurements under sinusoidal induction were carried out,

78 starting from quasi-static conditions (5 Hz for A and 20 Hz for B), up to f = 10 kHz for peak

79 polarization values J_p = 0.50, 1.0, 1.25 T. A broadband hysteresisgraph-wattmeter with digital

80 control of the induction waveform endowed with a 5kVA DC-20 kHz CROWN power amplifier

81 was employed. Sample heating was prevented by keeping the sample immersed in a water bath.

82   A remarkable outcome of these experiments is that the energy loss $W(f)$ does not depend, at all

83 frequencies, on the cross-sectional area of the sample (Fig. 1, SMC type A). The same occurs in the

84 SMC type B. This finding implies that grain-to-grain conductivity phenomena, either due to random

85 metallic contacts through the binder [14] or capacitive effects at high frequencies can be

86 disregarded from the viewpoint of losses. With the eddy current paths confined within the particles,

87 a good simplification is introduced in the loss analysis, because one can concentrate on the behavior

88 of the individual particles and their statistics. To start with, we calculate the classical loss

89 component W_{cl}, which in this case is the contribution that would originate if all particles were

90 magnetized at the same uniform rate imposed to the sample as a whole. Scanning electron

91 microscope images permit one to appreciate size and morphology of the particles and their

92 distribution. The cross-sectional area S_{part} of each particle is determined from a number of

93   micrographs using an image processing software. Their shape is irregular (Fig. 2), but, for the sake

94   of calculation, they are approximated as rectangles. The width and length of these equivalent

95   rectangles are identified by performing extended micrographic analysis and by taking the mean

96   values of particle area and aspect ratio. The Poisson equation for the magnetic field is then solved

97   by a finite element procedure, [12] in order to compute the eddy current loss in the rectangles. The

98   results for materials A and B are shown in Figs. 3 and 4, respectively, where the decomposition of

99   the measured loss W(f) into the hysteresis Whyst and excess Wexc(f) loss components is put in

100   evidence. Whyst is an experimental quantity, obtained by extrapolating the measured W(f) to f=0.

101   The strong reduction of Wcl(f) ensuing from the reduction of the particle size is apparent. By

102   associating it to a concurring reduction of Wexc(f), one gets that, in spite of higher Whyst, the total

103   loss W(f) in the fine-grained SMC type B becomes lower than in the coarse-grained SMC type A

104   beyond about 2 kHz.

105   As known, the excess loss arises because the dynamic magnetization process, like the

106   quasi-static one, is inhomogeneous in nature. However, since the eddy-current counterfields become

107   stronger with increasing frequency and they have to be compensated by the applied field in order to

108   keep a given magnetization rate $\dot{J}_p$, progressive homogenization of this process is concurrently

109   expected. This concept is made quantitative in terms of active magnetic objects (MOs) and their

110   frequency dependence by the statistical theory of losses [13], which provides the following general

111   expression for the excess loss

112

$$W_{exc}(J_p, f) = 2n_o V_o J_p \left(\sqrt{1 + \frac{16\sigma G S V_o}{n_o^2 V_o^2} f J_p} - 1 \right) \tag{1}$$

113   where $G = 0.1356$, S is the cross-sectional area of the sample, V_o is a parameter related to the

114   distribution of the local pinning fields for the MOs, and n_0 is the number of MOs that are

115   simultaneously active within the sample cross-section under quasi-static magnetization. It is

116   generally found in magnetic laminations that n_0 is at most a few units [13]. A basic tenet of the

117   theory is that the number of active MOs varies with frequency according to the linear law $n = n_0 +$

118   H_{exc}/V_0, where $H_{exc} = W_{exc}/4J_p$ is the excess field to be dynamically applied in order to counteract

119   the mesoscopic (i.e. circulating close to the moving domain walls) eddy current fields. By taking the

120   experimental $W_{exc}(f)$, as obtained by subtracting $W_{hyst} + W_{cl}(f)$ from the measured $W(f)$ values (see

121   Figs. 3 and 4), the n versus H_{exc} behavior is obtained, as shown for the A and B type SMCs in Fig. 5

122   for $J_p = 1$T. The experimental n_0 and V_o values found in this way are introduced in Eq. (1) and the

123   so calculated $W_{exc}(f)$, added to W_{hyst} and the previously obtained $W_{cl}(f)$, results into the fitting loss

124   curve for $W(f)$ shown in Figs. 3 and 4. A striking result of this analysis is that n0 is orders of

125   magnitude larger than in soft magnetic laminations. n_0 is a quantity that refers to the whole cross-

126   sectional area of the sample [13] and it appears here that the magnetization process in SMCs tends

127   to simultaneously invest a large number of particles at the same time already at low frequencies. It

128   can therefore be assumed that there should be at least one active magnetic object per particle at zero

129   excess field (i.e. under quasi-static excitation). If we take the type A SMC sample with S =25 mm2

130   and average grain-size area <s>2 = 0.0130 mm 2, one gets the mean number of particles <npart> in

131   the sample cross section <npart> = 1924, close to the number n0 of MOs (Fig. 5). For this material,

132   the observed dependence of n on the excess field (i.e. frequency), shown for Jp = 1.0 T in Fig. 5,

133   suggests that each particle should contain a few MOs, which will be dynamically activated on

134   increasing the frequency. The type B SMC shows a remarkably higher no value, as expected from a

135   correspondingly lower grain size. In both cases we observe that the condition no >> Hexc/Vo is

136   approximately satisfied in a good part of the investigated frequency range. A first order expansion

137   of Eq. (3) correspondingly provides Wexc~∝ f. This contrasts with usual Hexc/Vo >> no condition

138   already found at low frequencies in magnetic laminations [13], which leads to the typical Wexc~∝

139   f1/2 law.

140   III. CONCLUSIONS

141   The measurement of magnetic losses from DC to 10 kHz in commercial soft magnetic

142   composite materials and the analysis of the results -centered on the concept of loss decomposition-

143   highlights peculiar features of these materials. It is verified that the eddy currents are by and large

hindered from grain-to-grain circulation at all frequencies, with ensuing benefits from the viewpoint

of energy dissipation. This fact permits one to simplify the problem of loss calculation, whereby the

classical loss component can be analytically derived from knowledge of the distribution of the

particle size. A general formulation for the excess loss component, as provided by the statistical

theory of losses, can then be applied and shown to describe the experimental results and their

dependence on frequency. It is induced that the magnetization process in SMCs is characterized by

a good degree of homogenization already at very low magnetizing frequencies. The lack of

macroscopic eddy current patterns and the related counterfields eventually results, however, into a

faster than usual increase of the excess loss component with frequency and into its correspondingly

good contribution to the total loss up to the maximum investigated frequency of 10 kHz.

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Fig. 1: Energy loss versus frequency measured at peak polarization values J_p = 0.5 T, 1.0 T, 1.25 T in the type A soft magnetic composite (δ_{proto}=7450 kg/m^3). The results are obtained on two ring samples of cross-sectional areas $S_1 = 5 \times 5$ mm^2 and $S_2 = 2.5 \times 2.5$ mm^2, respectively.

Fig. 2: Micrograph for the type B SMC. The classical eddy current loss component Wcl(f) is calculated assimilating this structure with an array of rectangular grains.

Fig. 3: DC-10 kHz loss separation at J_p = 1.0 T in the SMC type A. The energy loss $W(f)$ (open symbols) is measured under controlled sinusoidal flux. The continuous fitting line is obtained by adding to the experimental hysteresis loss W_{hyst} the classical loss $W_{cl}(f)$, calculated with finite elements.

Fig. 4: Same as Fig. 3 for the SMC type B.

Fig. 5: Number of active magnetic objects n versus the excess field $H_{exc} = W_{exc}/4J_p$ at J_p = 1.0 T in the two investigated SMCs. The straight lines provides best fitting with the predicted relationship $n = n_0 + H_{exc}/V_0$.

Fig. 1
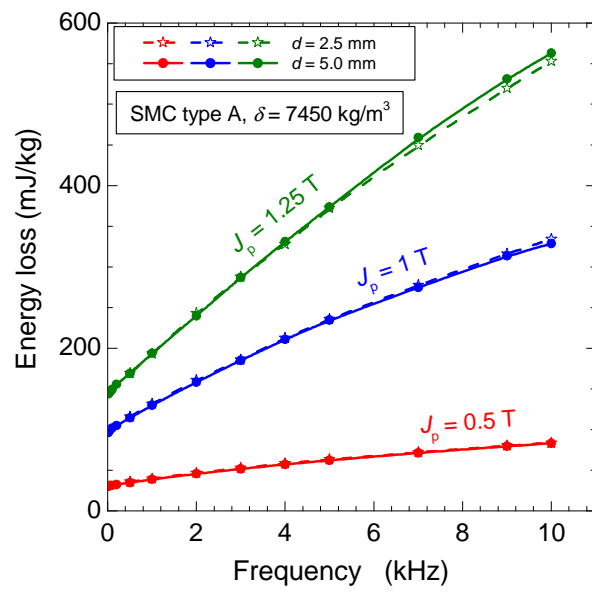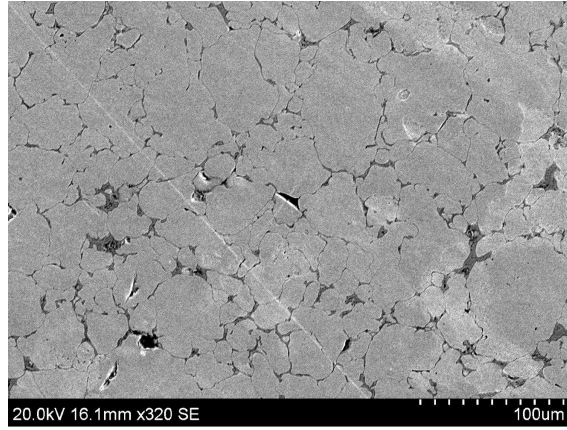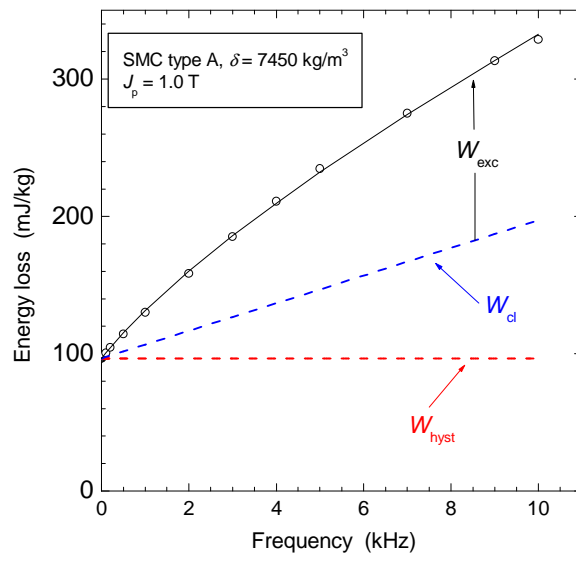
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20.0kV 16.1mm x320 SE   100um

Fig. 2

202
203
204

11

SMC type A, $\delta = 7450$ kg/m³
$J_p = 1.0$ T

W_{exc}

W_{cl}

W_{hyst}

Energy loss (mJ/kg)

Frequency (kHz)

205
206   **Fig. 3**
207

12

Fig. 4

208
209

210

Fig. 5

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212